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Active Control Technology at Nasa Langley Research Center

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NASA Langley has a long history of attacking important technical opportunities from a broad base of supporting disciplines. The research and development at Langley in this subject area range from the test tube to the test flight. The information covered here will range from the development of innovative new materials, sensors and actuators, to the incorporation of smart sensors and actuators in practical devices, to the optimization of the location of these devices, to, finally, a wide variety of applications of these devices utilizing Langley's facilities and expertise.

Advanced materials are being developed for sensors and actuators, as well as polymers for integrating smart devices into composite structures. Contributions reside in three key areas: computational materials; advanced piezoelectric materials; and integrated composite structures.

The computational materials effort is focused on developing predictive tools for the efficient design of new materials with the appropriate combination of properties for next generation smart airframe systems. Research in the area of advanced piezoelectrics includes optimizing the efficiency, force output, use temperature, and energy transfer between the structure and device for both ceramic and polymeric materials. For structural health monitoring, advanced non-destructive techniques including fiber optics are being developed for detection of delaminations, cracks and environmental deterioration in aircraft structures.

Innovative fabrication techniques for processing structural composites with sensor and actuator integration are being developed. A majority of this research will be completed for specific applications including the fabrication of a composite panel with embedded shape memory alloys (SMA) for reducing sonic fatigue in aircraft structures. The research in each of these key areas has been designed to meet application needs of the customers including aeroelastic tailoring, noise cancellation, and laminar flow control. Within this section, a portion of the ongoing research in each of the areas of materials research is highlighted.

The application of actuators, sensors, and controllers to alter the performance of structures has become a viable tool for designers. Controlled structures technology has matured and many new sensor and actuator types have been developed over the last two decades. Most examples of controlled structures involve surface mounting or bonding of the sensors and actuators. This approach often carries the least risk as the passive structural load paths are unaltered and failed components can be readily identified and corrected. Surface mounting is appropriate for inertial proof-mass actuators and for displacement/force actuators connecting the controlled structure to ground. However strain actuators, which create a relative displacement within the structure, are usually most effective when embedded into the structural elements. Structural integration of the actuators, sensors, power and data electrical buses, and perhaps the controller electronics should also lead to more robust and durable controlled structural systems.

Researchers at NASA Langley Research Center have extensive experience using active structural acoustic control (ASAC) for aircraft interior noise reduction. One aspect of ASAC involves the selection of optimum locations for microphone sensors and force actuators. We have investigated the importance of sensor/actuator selection, optimization techniques, and have produced some unique experimental and numerical results.

Optimized architectures are critical to the success of ASAC. For laboratory tests, with simplified acoustic sources and environments, the best locations possibly can be selected by inspection or modal methods. For small numbers of actuators and sensors, the evaluation of all possible combinations may even be practical. However, for complicated acoustic enclosures, such as an aircraft fuselage, and for reasonable numbers of candidate actuators and sensors, a combinatorial optimization method such as tabu search can improve the quality of the locations selected.

The application of smart sensors and actuators has only been limited by the human imagination. We will give a taste of some very important practical applications of these materials. All of these applications have been worked cooperatively with other organizations to take advantage of each organizations skills and resources.

NASA Langley has a long history of attacking important technical opportunities from a broad base of supporting disciplines. The research and development at Langley in this subject area range from the test tube to the test flight. The information covered here will range from the development of innovative new materials, sensors and actuators, to the incorporation of smart sensors and actuators in practical devices, to the optimization of the location of these devices, to, finally, a wide variety of applications of these devices utilizing Langley's facilities and expertise.

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1. MATERIALS

Advanced materials are being developed for sensors and actuators, as well as polymers for integrating smart devices into composite structures[1]. Contributions reside in three key areas: computational materials; advanced piezoelectric materials; and integrated composite structures.

The computational materials effort is focused on developing predictive tools for the efficient design of new materials with the appropriate combination of properties for next generation smart airframe systems. Research in the area of advanced piezoelectrics includes optimizing the efficiency, force output, use temperature, and energy transfer between the structure and device for both ceramic and polymeric materials. For structural health monitoring, advanced non-destructive techniques including fiber optics are being developed for detection of delaminations, cracks and environmental deterioration in aircraft structures. The research in each of these key areas has been designed to meet application needs of the customers including aeroelastic tailoring, noise cancellation, and laminar flow control. Within this section, a portion of the ongoing research in each of the areas of materials research is highlighted.

1.1 COMPUTATIONAL MATERIALS

Developments in a number of areas of aeronautics are currently materials-limited. These areas include the creation of efficient, lightweight structures, some aspects of propulsion, noise and vibration abatement, and active controls. Recent, rapid increases in computer power and improvements in computational techniques open the way to the use of simulations in the development of new materials. At NASA-LaRC, computer-aided design of materials has concentrated on two classes of materials: high performance continuous-fiber reinforced polymer matrix composites and piezoelectric films from high temperature polyimides.

An integrated, predictive computer model is being developed to bridge the microscopic and macroscopic descriptions of polymer composites. This model will significantly reduce development costs by bringing physical and microstructural information into the realm of the design engineer. The range of length and time scales involved is huge, and different scientific and engineering disciplines are involved. Models at each level require experimental verification and must connect with models at adjacent levels.

1.2 ADVANCED PIEZOELECTRIC MATERIALS

Piezoelectric Polymers

A research problem that combines both computational and experimental studies is the development of high performance, piezoelectric polymeric materials. The piezoelectric response of a polymer is a function of its dipole concentration, the degree of dipole orientation, and the mechanical properties of the polymer. Currently, fluoropolymers such as polyvinylidene fluoride (PVDF) are the state of the art in piezoelectric polymers. The development of other classes of piezoelectric polymers could provide enabling materials technology for a variety of aerospace and commercial applications. Polyimides are of particular interest due to their high temperature stability and the ease with which various polar pendant groups may be incorporated[2]. Particularly interesting is the potential use of piezoelectric polyimides in MEMS devices as fluoropolymers do not possess the chemical resistance or thermal stability necessary to withstand conventional MEMS processing

In order to induce a piezoelectric response, the polymer is poled by applying an electric field (E_p = 100 MV/m) across the thickness of the polymer at an elevated temperature sufficient to allow mobility of the molecular dipoles. The dipoles are aligned with the applied field and will partially retain the induced polarization when the temperature is lowered below the glass transition temperature in the presence of the field. The resulting remnant polarization is proportional to the level of piezoelectricity.

To computationally simulate the experimental poling process, semi-empirical molecular orbital calculations on model segments of the polymers were used to obtain the electron distributions and potential energy surfaces of the segments. Calculated dipole moments of the model segments were compared with experimental data whenever possible. In addition, the torsional barriers were of interest because they dictate the flexibility of the polymer backbone and hence the ability of the dipoles to orient in response to an external field. A modified force field for use in molecular dynamics simulations was then created. A five unit long polymer was built and packed into a cell with three-dimensional periodic boundary conditions at the experimental density. The temperature and electric field were scaled to bring the poling response into the simulation time scale (200 picoseconds.) From this model, dielectric relaxation strengths were calculated which are in excellent agreement with experimental results, indicating that the computational model can be used as a reliable tool to guide the synthesis of new piezoelectric polymers[3].

Ongoing research, guided by computational models, should provide improved understanding of the requirements for heightened piezoelectric response and the ability to rapidly evaluate candidate structures in consultation with synthetic polymer chemists.

High-Displacement Piezoelectric Ceramic Actuators

Piezoelectric devices have been identified as a promising actuator technology for the implementation of active boundary layer control, high bandwidth noise suppression and aeroservoelastic tailoring. However, many potential aerospace applications require displacement performance larger than what is achievable in conventional piezoelectrics. Recently LaRC researchers have developed two high-displacement piezoelectric actuator technologies, RAINBOW (Reduced And INternally-Biased Oxide Wafer) and THUNDER (THin layer composite UNimorph ferroelectric DrivER and sensor) to meet these requirements. These devices are unimorph-type actuators which consist of a piezoelectric ceramic layer bonded to one or more non-piezoelectric secondary layers. Because of the use of elevated temperatures during processing, internal stresses are created in the structures which significantly enhance displacement through the thickness of the devices. The reader is referred to the literature for more information on RAINBOW [4-6] and THUNDER [7-9] devices and their application.

Currently, the processing and characterization of these high-displacement actuators are under investigation. One recent characterization study involved the effects of electric field, load and frequency on the displacement properties of rectangular THUNDER devices. Results showed that individual actuators were capable of free displacements in excess of 3 mm when tested at ± 9 kV/cm. Increasing device stiffness through metal selection and thickness resulted in improved load-bearing performance at the expense of displacement, allowing devices to be designed with a range of performance capabilities.

1.3 ATTACH PROJECT

The Airfoil THUNDER Testing to Ascertain Characteristics (ATTACH) project[9,10] was a feasibility study that focused on identifying (1) the material characteristics, such as creep, hysteresis, and fatigue, and (2) the airfoil shaping effectiveness of the new THUNDER piezoelectric technology under aerodynamic loading. Characterization of the material behavior of THUNDER was the objective for Phase I, while Phase II examined its ability to reduce drag over an airfoil. The following sections present both the approach and preliminary findings of both phases of testing.

The concept behind drag reduction via airfoil shaping with a THUNDER wafer affixed to the upper surface of a symmetric airfoil and covered with a flexible membrane is shown in Figure 1. Figure 1a shows the typical flow field with the airfoil set at a small positive angle of attack and the THUNDER wafer unactuated. As identified in the figure, the flow remains attached to the upper surface of this nominal airfoil configuration only across a small region near the leading edge. The flow then separates because of the presence of a large adverse pressure gradient. Figure 1b shows the anticipated flow field over the same airfoil with the THUNDER wafer actuated up to meet the flow. With such an increase in camber of the upper surface, the onset of the large adverse pressure gradient would be delayed, allowing for a longer attachment region.

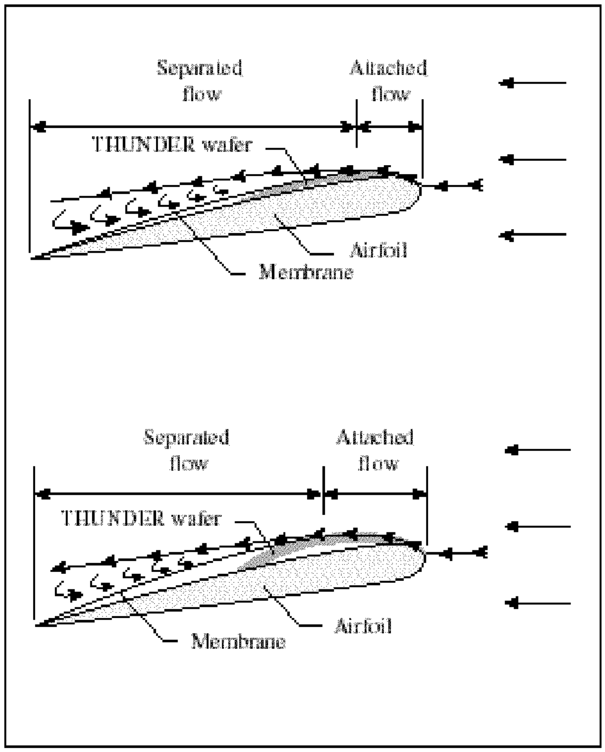

Figure 1. Concept for drag reduction via airfoil shaping with THUNDER.

The testbed used for both phases of testing in the ATTACH project was the 0.25-inch thick, 1.5-inch wide, 5-inch long, generic, roughly symmetric airfoil shown in Figure 2. This airfoil was supported by two 0.25-inch thick, 10-inch long sidewalls in the 6- by 6-inch test section of a tabletop wind tunnel. These sidewall inserts extended through 85% of the length of the test section, creating a nearly two-dimensional flow condition. A single 1.5-inch wide, 2.5-inch long rectangular wafer of THUNDER was placed near the leading edge of the airfoil to act as the first half of the upper surface. To smooth the airfoil/wafer interface, a sheet of thin fiberglass material was wrapped over the upper surface of the airfoil/wafer combination and held in place by a flexible latex membrane. A photograph of the installed model is shown in Figure 3.

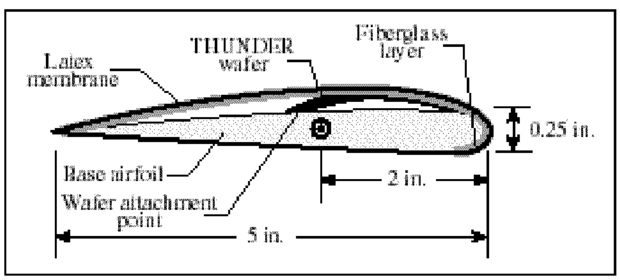

Figure 2. ATTACH testbed.

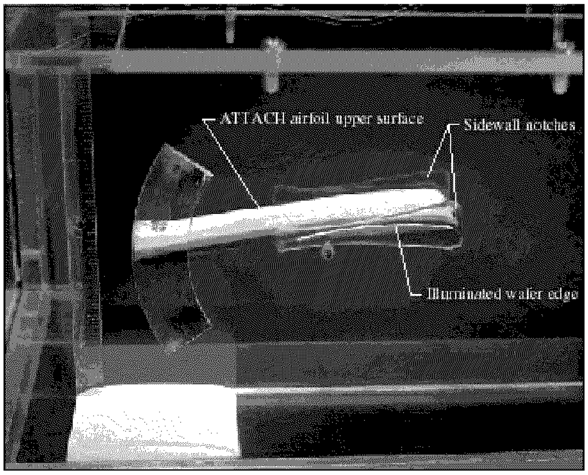

Figure 3. Photograph of the ATTACH model in the wind-tunnel test section.

ATTACH Phase I testing

The initial series of tests conducted during the ATTACH project were performed to identify the creep, hysteresis, and fatigue characteristics of a THUNDER wafer under aerodynamic loading. For this experiment, a total of 60 conditions were tested, consisting of combinations of the following parameters: five angles of attack (-2°, 0°, +2°, +4°, +6°), four steady-state input voltages (-102 V, +102 V, -170 V, +170 V), and three tunnel velocities (wind-off, 20 m/s, 35 m/s).

The data obtained during this experiment conclusively identified the presence of both creep and hysteresis of the wafer under wind-on (loaded) and wind-off (unloaded) conditions. After two weeks of testing, the performance of the wafer began to noticeably degrade. During subsequent examination, no visible flaws were found, but a 33% drop in capacitance was discovered, and repoling returned the wafer to its full capabilities. Thus, similar to other piezoelectric adaptive materials, the performance of THUNDER appears to be a function of capacitance.

ATTACH Phase II testing

To assess the ability of the THUNDER wafer to reduce drag over the airfoil, tests were conducted at the 40 wind-on conditions previously described for Phase I. For purposes of this feasibility study, it was assumed that variations in drag were directly proportional to velocity changes in the wake of the model. Comparisons of wake velocity for different test conditions, therefore, provided qualitative indications of the drag reducing potential of this piezoelectric actuator for this subscale model. Velocity measurements were taken by traversing a hot film anemometer velocity probe in 0.125-inch increments through the center of the test section sufficiently aft of the airfoil trailing edge to allow the wake to return to tunnel static pressure.

Results from this phase of testing were consistent with the results from Phase I. Positive applied voltages, which expanded the upper surface of the airfoil, had the effect of increasing the velocity in the wake, a result consistent with a decrease in drag. Increases in tunnel velocity and/or model angle of attack produced even greater expansions of the upper surface and, therefore, larger wake velocities at the positive voltages. Negative applied voltages produced the opposite effect. These results were obtained using only 32% of the maximum unloaded capability of the wafer. Thus, greater drag reductions would be expected if that percentage is increased.

The results of this research effort indicate that the new THUNDER actuator technology is a promising candidate for future airfoil shaping investigations. Despite decreases in the displacements of the wafer due to aerodynamic loading, noticeable drag reductions were obtained.

1.4 SHAPE MEMORY ALLOYS (SMAs)

Interior noise and sonic fatigue are important issues in the development and design of advanced subsonic and supersonic aircraft. Conventional aircraft typically employ passive treatments, such as constrained layer damping and acoustic absorption material, to reduce the structural response and resulting acoustic levels in the aircraft interior. These techniques require significant addition of mass and only attenuate relatively high frequency noise transmitted through the fuselage. Adaptive and/or active methods of controlling the structural acoustic response of panels to reduce the transmitted noise may be accomplished with the use of SMA hybrid composite panels. These panels have the potential to offer improved thermal buckling/post buckling behavior, dynamic response, fatigue life, and structural acoustic response.

Initial work in the fabrication of integrated composites has focused on the manufacture of E-glass/ Fiberite 934 epoxy panels with embedded shape memory alloys. Quasi-isotropic panels with unstrained SMAs embedded in the zero degree direction have been successfully fabricated. Since 1/2-inch wide Nitinol strips were not available, five 0.10 inch wide, 5 mil thick rectangular Nitinol ribbons were butted together side to side with a spacing of 1/2 inch between sets. The SMA strips were heated to 250°F for an hour after being cut and prior to being embedded to recover any initial strain that may have developed from being shipped wound on a spool. The SMA composite panels were processed using the standard 934-epoxy autoclave cure cycle (2hr @ 350°F, 100 psi). Test specimens machined from a cured hybrid panel are shown in Figure 4. Future panels will be fabricated with prestrained SMA strips. These panels require tooling which will restrain the SMA strips from contracting during the thermal cure. Panels with bi-directional (0°/90°) SMAs as well as hybrid built-up structure will also be fabricated.

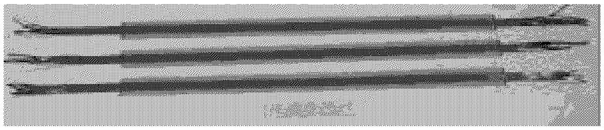

Figure 4. Test specimens machined from an E-glass/ 934 epoxy panel with embedded Nitinol shape memory alloy ribbons.

2. INTEGRATION ISSUES FOR HIGH-STRAIN

Strain actuators, used to induce a relative structural displacement, are most effective when integrally embedded into the host structure. The section summarizes progress and challenges in the field of embedding smart materials into structures[11]. The difficulties of embedding active elements within composite structures are described from a system design perspective. Issues associated with the application of strain actuators in primary aircraft structure are discussed. Development of new embedding technology to combat the difficulties associated with high strain applications is advocated.

The application of actuators, sensors, and controllers to alter the performance of structures has become a viable tool for designers. Controlled structures technology has matured and many new sensor and actuator types have been developed over the last two decades. Most examples of controlled structures involve surface mounting or bonding of the sensors and actuators. This approach often carries the least risk as the passive structural load paths are unaltered and failed components can be readily identified and corrected. Surface mounting is appropriate for inertial proof-mass actuators and for displacement/force actuators connecting the controlled structure to ground. However strain actuators, which create a relative displacement within the structure, are usually most effective when embedded into the structural elements.

Numerous advances have and continue to be made in developing "solid-state" strain actuators and sensors. In particular, shape memory alloys, piezoelectrics (including piezo fiber composites and single crystal materials), and magnetostrictive materials have been successfully demonstrated as strain actuators. Except for simple structural geometries such as beams and plates, surface mounting of strain actuators leads to less control authority than when they are embedded and impedance matched to the host structure. Structural integration of the actuators, sensors, power and data electrical buses, and perhaps the controller electronics should also lead to more robust and durable controlled structural systems.

Difficulties range from electronic circuit failures due to dielectric breakdown and arcing, breaking of the ceramic wafer and electronic leads, low performance due to internal heating and impedance mismatches, and compromised structural integrity due to microcracking and macrocracking in the composite structure. These complications were encountered in low to moderate strain level applications. Structural embedding is even more problematic when high strain, high stress applications are pursued. One such application, is the active load alleviation of aircraft. If an active wingbox structure could be designed, significant weight reduction could be achieved in the wingbox structure while simultaneously improving ride comfort and fatigue life.

3. OPTIMAL SENSOR/ACTUATOR LOCATIONS FOR ACTIVE STRUCTURAL ACOUSTIC CONTROL

Researchers at NASA Langley Research Center have extensive experience using active structural acoustic control (ASAC) for aircraft interior noise reduction. One aspect of ASAC involves the selection of optimum locations for microphone sensors and force actuators.

Active acoustic control, or the use of one acoustic source (or secondary source) to cancel another (or primary source), has a long history. In a recent survey paper, Fuller and Von Flotow[12] describe practical demonstrations of the technique as early as 1953 and a U.S. patent as early as 1936. In addition, these authors describe several commercially successful active noise and vibration control systems in use today. Their paper is highly recommended to any reader who desires a complete discussion of active acoustic control and its practical uses.

The scope of the present section is limited to active structural acoustic control (ASAC), with a focus on aircraft interior noise control research conducted at NASA Langley Research Center. The most obvious difference between the ASAC system and early acoustic control systems is that ASAC uses structural actuators like shakers or piezoelectric (PZT) patches attached to the aircraft fuselage rather than acoustic actuators like loudspeakers inside the fuselage. The ASAC concept is attractive because the structural actuators are more effective by weight and consume less interior volume than competing active or passive noise control options.[13]

One area of ASAC research is the determination of optimal locations for actuators and sensors. Early theoretical investigations[14-16] established the importance of actuator and sensor architecture and suggested optimization strategies and goals. In their survey paper, Fuller and Von Flotow[12] describe the actuator location problem from a practical standpoint. They note that researchers recommend a modal method, such that actuators are placed to excite a selected structural mode and sensors are placed to observe each important acoustic mode.

3.1 OPTIMIZATION OVERVIEW

Given a set of N_a actuator locations, the goal of an optimization run is to identify a subset of N_c locations that provides the best performance (e.g., reduces interior noise). Several combinatorial optimization methods, such as simulated annealing, genetic algorithms, and tabu search, are available. Tabu search was selected for use in the present study, based on previous experience.[16]

To apply a tabu search algorithm one must define a state space, a method for moving from state to state, a neighborhood for each state, and a cost function to minimize. For the actuator selection problem, the set of all possible subsets of size N_c chosen from N_a actuators is the state space. To bound the problem, the subset size N_c is constant for each search. An initial state can be prescribed by the user or can be generated randomly. At any given state, the subset N_c, of actuators that represent that state are flagged as "on;" the remaining actuators are flagged as "off." A move changes the state by turning one actuator off and one on. A neighborhood is the set of all states that are one move away from the current state. Finally, the cost function is based on the noise reduction estimate for the subset of actuators that are turned on.

Each iteration of the tabu search algorithm involves evaluating the cost function for each subset of actuators in the neighborhood of the current state. The move that improves the cost function the most is accepted. If no improving move is identified, then the move that degrades the cost function the least is accepted. The algorithm continues for a predetermined number of iterations. Cycling is avoided by maintaining a list (called the tabu list) of all accepted moves. The algorithm is prohibited from reversing any move on the tabu list. An exception can be made if the move is old or if the move produces a state that is clearly better than any previous state. The algorithm terminates after reporting the best state that was encountered during the entire optimization procedure.

3.2 SIMULATED ASAC

In this section, tabu search is applied to a simplified model of the ASAC problem. This simulation serves several purposes. First, the simulation illustrates the method and indicates the potential for reducing aircraft interior noise. Secondly, the relationship between the shell vibration level and the interior noise level is explored.

Problem Statement

Assume that an aircraft fuselage is represented as a cylinder with rigid end caps (fig. 5) and that a propeller is represented as a point monopole with a frequency equal to some multiple of the blade passage frequency. Piezoelectric actuators bonded to the fuselage skin are represented as line force distributions in the x and • directions. With this simplified model, the point monopole produces predictable pressure waves that are exterior to the cylinder. These periodic pressure changes cause predictable structural vibrations in the cylinder wall and predictable noise levels in the interior space. Using the PZT actuators to modify the vibration of the cylinder can dramatically reduce the interior noise level at any discrete microphone location. For a given set of microphones and a given set of actuator locations, the control forces that minimize the acoustic response are known.[14] However, methods for choosing good locations for the microphones and the actuators are needed.[17]

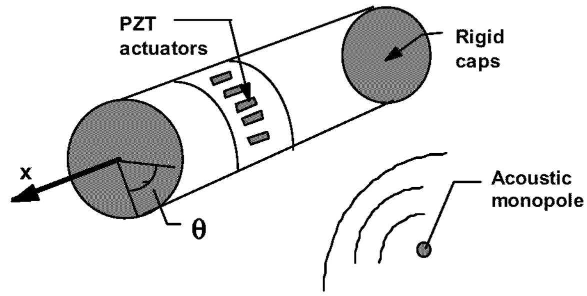

Figure 5. Schematic of simplified cylinder, point source, and actuator model.

Results

The results from the simulated studies are encouraging. For varying numbers of possible locations, subset sizes, source frequencies, and sets of interior microphones, the same trends are observed. Namely, the subset of actuators selected by tabu search to reduce interior noise tends to reduce cylinder vibration as well. The 16 best locations are chosen from a set of 102 possible locations. The initial set of 16 actuators reduces the noise by 13 dB but increases the cylinder vibration by 4 dB. However, after 15 iterations, both noise and vibration levels are reduced dramatically. Fifteen additional iterations produce no significant improvement. By adjusting the number of actuators up or down from 16, the noise-reduction goals can be satisfied without an increase in vibration and without exceeding the force capacity of the PZT actuators.

3.3 EXPERIMENTAL ASAC STUDIES

The simulation studies indicate the importance of actuator location in active structural acoustic control. Experimental tests are a necessary next step. In these tests, the transfer matrix is constructed by using measured data, and the effectiveness of selected locations can be verified experimentally. More complete descriptions and discussion of results are available in the references.

Langley Composite Cylinder

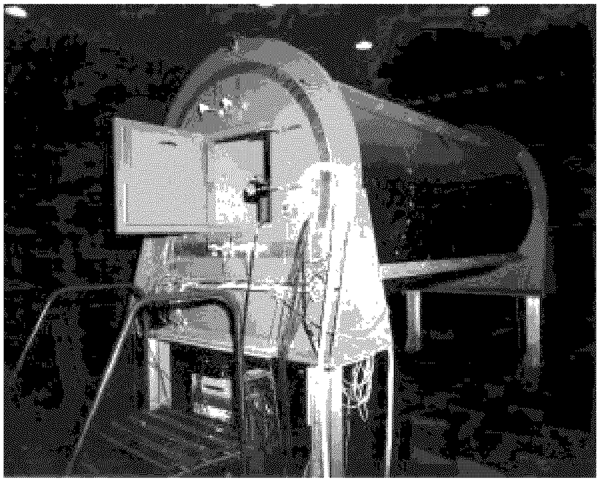

Figure 6. Composite cylinder at NASA Langley

The composite fuselage model is shown in figure 6. The cylinder is 3.6 m long and 1.68 m in diameter. The outer shell is graphite epoxy, which is stiffened by composite stringers and ring frames. The interior has a plywood floor and inner trim panels that are attached to the ring frame. The primary source is a 100-W electrodynamic loudspeaker that is mounted 0.3 m from the exterior sidewall. The secondary source is a subset of the eight piezoelectric actuators bonded to the interior trim panels. (See fig. 7)

Six boom-mounted microphones were used to collect data. The boom can translate and rotate to collect sound pressure levels at 462 data points within the cylinder volume. Two of the cross sections surveyed by the boom microphones are indicated in figure 7.

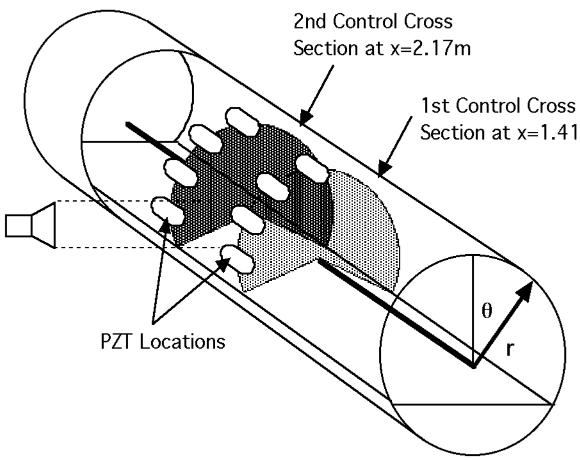

Figure 7. Schematic of composite cylinder

Six boom-mounted microphones were used to collect data. The boom can translate and rotate to collect sound pressure levels at 462 data points within the cylinder volume. Two of the cross sections surveyed by the boom microphones are indicated in figure 7.

The interior noise data are collected for three different frequencies: 210, 230, and 275 Hz. For each frequency, the data are collected for the primary source alone and then for the secondary source alone by using a single unit input separately at each of the eight actuators. The three frequencies are well chosen. The first (i.e., 210 Hz) represents a case in which a single dominant acoustic mode is easily controlled with a single structural mode. The other two frequencies represent cases in which no particular acoustic or structural mode is dominant or in which several modes are important.

Single Frequency Optimization Method

The goal of the optimization is to pick the four best actuators and the eight best sensors for use in active noise control. Tabu search may be used to select four out of eight actuators.

The goal of the composite cylinder laboratory tests is to reduce noise at all 462 microphone locations by using a linear control law with feedback from 8 of the 462 microphones.[18] Clearly, tabu search must identify microphones that are able to observe all important acoustic modes. Moreover, some linear combination of the selected actuator responses must approximately cancel out the primary response.

The initial tabu search results did not meet our expectations. The optimization procedure did identify architecture with greater noise reduction potential than any of those found by random trials. However, inspection of the contour maps of the interior noise indicates that many of the selected sensors are in low noise areas where the change in noise as a result of the control system is small.

To select better actuator/sensor combinations, the tabu search cost function was modified to include a variance measure in addition to a noise reduction measure. Both absolute value and sum of variances were tried with equal success.[19]

Composite Cylinder Results

The composite cylinder model was used to test the selected actuator and sensor locations. The four best and four worst actuators were tested. For each actuator set, the eight best sensors were determined by tabu search. These test results are compared with previous test results in which the actuators and sensors were selected by using modal methods.

Test results are reported in reference 18 and summarized here. As expected, the control forces predicted in the optimization procedure and the noise reduction predicted do not match the observed control forces or noise reduction. Possible explanations for the differences include premature convergence of the optimal control algorithm and errors in the measured transfer functions. However, the trends are well predicted. For example, the noise reductions observed for the case in which the frequency was equal to 210 Hz are not sensitive to actuator set selection. This case has one dominant acoustic mode. On the other hand, the noise reduction observed for the cases with frequencies of 230 Hz and 275 Hz shows a strong dependence on actuator location.

The observed noise reduction is less than predicted. However, the four best actuators provide 3.5 dB more noise reduction than the four worst and, in addition, perform better than those selected by modal methods. This finding suggests that the tabu search procedure is particularly effective in those cases in which tradeoffs between several important acoustic modes must be considered.

3.4 OPTIMIZATION SUMMARY

Clearly, optimized architectures are critical to the success of ASAC. For laboratory tests, with simplified acoustic sources and environments, inspection or modal methods possibly can select the best locations. For small numbers of actuators and sensors, the evaluation of all possible combinations may even be practical. However, for complicated acoustic enclosures, such as an aircraft fuselage, and for reasonable numbers of candidate actuators and sensors, a combinatorial optimization method such as tabu search can improve the quality of the locations selected.

One weakness in the method is the need for accurate models of the closed loop performance of the control system. For now, the control system is modeled by using a linear transfer function. This transfer function is expensive to produce. The transfer function can be created experimentally, in which case the unit response must be measured for a large number of candidate actuator and sensor locations. On the other hand, the transfer function can be simulated, in which case a highly accurate model of the acoustic source and enclosure is required.

It is expected that this research on optimum sensor and actuator location for noise reduction will serve as a pathfinder for other applications like flow control or aeroelastic control.

4.0 APPLICATION OF SMART MATERIALS

The application of smart sensors and actuators has only been limited by the human imagination[20]. This section will give you a taste of some very important practical applications of these materials. All of these applications have been worked cooperatively with other organizations to take advantage of each organization's skills and resources. These applications include the Smart Wing program, and the Active Twist Rotor program.

4.1 DARPA/ AFRL/ NASA SMART WING PROGRAM

The overall objective of the DARPA/ Air Force Research Labs/ NASA Smart Wing program is to design, develop and demonstrate the use smart materials and structures to improve the aerodynamic performance of military aircraft including improvements in lift to drag ratio, maneuver capabilities and aeroelastic effects. The approach includes: 1) designing, fabricating and testing scaled semi-span and full-span wind-tunnel models; 2) addressing power, reliability, packaging and system integration issues; and 3) laying the ground work for technology transition in a potential follow-on program. An overview of the program is presented in reference 21. The Smart Wing program is led by the Northrop Grumman Corporation who was awarded DARPA contracts for Phase I, which began in March 1997, and Phase II, which began in August 1998. Phase I and Phase II contracts are being monitored by the Air Force Research Laboratory (AFRL) at Wright Patterson Air Force Base. Wind tunnel testing during the program is being performed at the NASA LaRC TDT via a Memorandum of Agreement between NASA LaRC and Northrop Grumman. In addition, the administrative responsibilities of the program are being coordinated through an Interagency Agreement between the AFRL and NASA LaRC. Other members of the large team of researchers on the program include: Lockheed Martin Astronautics and Control Systems; Naval Research Labs; Mission Research Corporation; Rockwell Science Center; Fiber & Sensor Technologies, Inc.; Etrema Products, Inc.; SRI International; University of California, Los Angeles; Georgia Institute of Technology, and the University of Texas at Arlington.

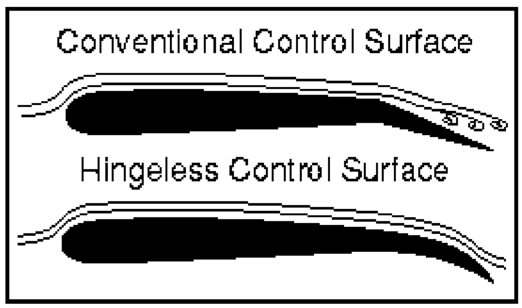

Figure 8: Hingeless control surface concept

During Phase I of the program, a 16% scaled semi-span model ("Smart Wing") of the F/A-18 aircraft was designed and fabricated incorporating three key features: 1) hingeless, smoothly contoured trailing edge control surfaces, 2) variable spanwise wing twist and 3) fiber optic pressure and strain transducers. Another identically scaled model of conventional construction (hinged control surfaces and no wing twist) was fabricated and used as a baseline for comparison. On the Smart Wing model, the hingeless aileron and flap are actuated using shape memory alloy (SMA) tendons. As shown in Figure 8, the hingeless control surface concept reduces the separated flow region on the wing thereby increasing lift to drag ratio. On the Smart Wing model, wing twist is accomplished through the use of two shape memory alloy-actuated torque tubes. The schematic in Figure 9 depicts the wing twist concept.

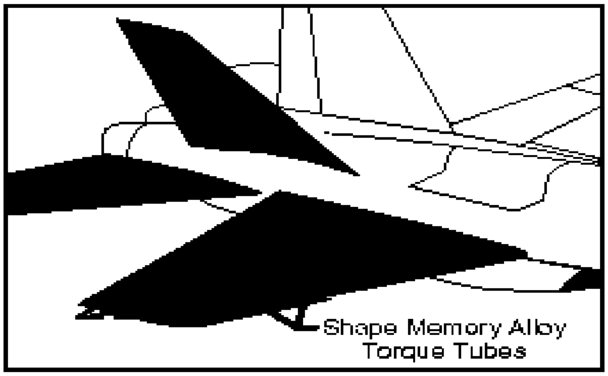

Figure 9: Wing twist concept

The first wind-tunnel test in Phase I took place at the LaRC TDT in May 1996. A photograph of the Smart Wing model in the TDT is shown in Figure 10. During the test, 1.25 degrees of twist was achieved using the SMA torque tubes resulting in approximately an 8% improvement in rolling moment. The hingeless control surfaces deployed up to 10 degrees, providing between an 8 and 18% increase in rolling moment and approximately an 8% increase in lift. A complete summary of wind-tunnel test results is presented in reference 22. The second wind-tunnel test of Phase I took place in June-July 1998 using a redesigned torque tube and hingeless control surfaces. During this test, 5 degrees of twist was achieved resulting in a 15% increase in rolling moment. In addition, 10 degrees of deflection on the hingeless control surfaces was obtained with improved controllability and repeatability. Phase II of the Smart Wing program includes plans to further mature the technologies developed in Phase I as well as investigate new actuation concepts. Two wind-tunnel tests in the LaRC TDT are currently planned for Phase II.

Figure 10: Smart Wing model in the LaRC TDT

4.2 ACTIVE TWIST ROTOR RESEARCH

Recent analytical and experimental investigations[23-28] indicate that helicopter rotor blades containing embedded interdigitated-electrode poled, piezoelectric fiber composite layers (*active fiber composites*) should be capable of meeting the performance requirements necessary for a practical individual blade control (IBC) system[29]. For this reason, twist-actuated helicopter rotor systems using active fiber composites (AFC) have become the focus of several advanced rotor blade control research activities at NASA Langley Research Center.

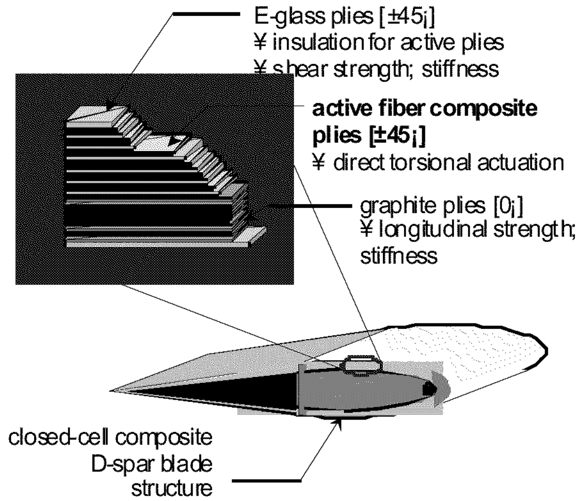

Figure 11: Full-scale active fiber composite rotor blade concept.

An example of the active fiber composite rotor blade concept is illustrated in Figure 11. Piezoelectric AFC plies are oriented at ±45 degrees within the primary structure of the blade in order to generate dynamic blade twisting. Mathematical models indicate that from 1 to 2 degrees of twist amplitude over a relatively wide frequency bandwidth are possible using the high strain actuation capabilities of the AFC plies. Systems studies also indicate that this magnitude of twist actuation authority should be possible at full-scale with only modest increases in blade weight and low levels of power consumption. AFC actuators utilize an interdigitated electrode poling method (IDE)[30] to generate large directional actuation strains in the actuator plane. Piezoelectric materials in fiber form are also used, and are protected by an epoxy matrix which improves the durability characteristics of the actuator.[31,32] Combining both of these technologies results in a high performance piezoelectric actuator lamina with induced stress, endurance, and conformability characteristics superior to typical monolithic piezoceramic actuators.

Aeroelastic Modeling of Active Fiber Composite Rotors

To investigate the potential of active fiber composite rotors, two active twist rotor mathematical modeling methods have been developed at NASA Langley. The first of these is a simple mathematical aeroelasticity model for composite helicopter rotor blades incorporating anisotropic embedded piezoceramic actuators. The computer implementation of this model, the Piezoelectric Twist Rotor Analysis (PETRA), has been created for use with the MATLAB[33] numerical analysis program and is ideally suited for conceptual active twist rotor design and optimization studies[25,26,28]. A procedure for using a commercially available comprehensive rotorcraft computer code (CAMRAD II[34]) for active twist rotor studies has also been developed. This allows active twist rotor numerical studies to be performed using a detailed state-of-the-art rotorcraft aerodynamics and structural dynamics model. Some examples of numerical results obtained using both active twist rotor blade analysis methods are described below.

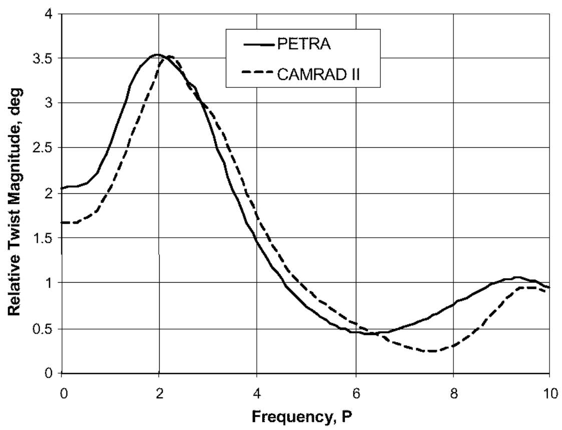

Figure 12: Hovering flight twist actuation frequency response for a full-scale active twist rotor blade concept. (Frequency scale is in multiples of the fundamental rotor frequency, P.)

Analytically determined hovering flight twist actuation frequency response curves for a full-scale active twist rotor blade concept similar to that depicted in Figure 11 are shown in Figure 12. These calculations were performed for a representative one-g hovering flight condition. Results using both PETRA and CAMRAD II are shown for comparison. Large amplitudes of blade twisting (greater than 2 degrees from center of rotation to the blade tip) are indicated with both modeling methods. The twist amplitude and bandwidth behavior shown here would be sufficient for many IBC applications, and vertical hub shear vibration reduction in particular. Agreement between the two analytical methods is also extremely good and shows that the fundamental active twist rotor dynamics are being modeled consistently.

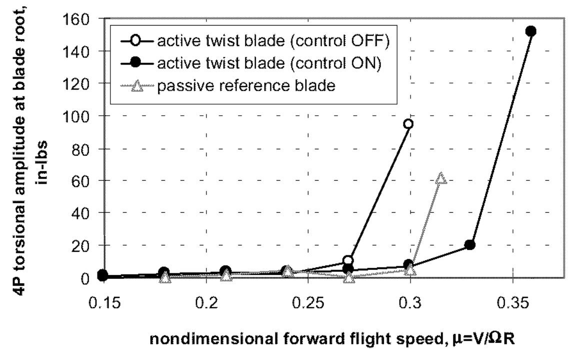

Figure 13: Suppression of dynamic stall induced torsional vibrations through active twist control. Constant rotor thrust condition shown.

An example of the predicted capability of active fiber composite rotor blades to alleviate stall on helicopter rotors is shown in Figure 13 [28]. Rapid buildup of torsional vibratory loads due to stall severely restricts the maximum lift and forward flight speed capabilities of conventional helicopters. Vibration trends with increasing flight speed are shown for a conceptual full-scale active twist rotor blade with and without twist actuation control. Trends for a conventional, passive-structure blade are also shown as a reference. The rapid rise in dynamic stall-induced torsional vibratory loads for the active twist rotor blade using twist control has been effectively delayed by approximately 10% in nondimensional flight speed with respect to the baseline blade and by as much as 22% with respect to the active fiber composite blade with no twist control. This delay in torsional vibration buildup represents a significant expansion of the dynamic stall limited operational flight envelope of the helicopter rotor.

Testing Active Fiber Composites Helicopter Rotor Blades

Based on these and other promising analytical findings, a cooperative effort between NASA, the Army Research Laboratory, and the Massachusetts Institute of Technology has been initiated to construct an aeroelastically-scaled active twist rotor research model suitable for testing in the heavy gas environment of the Langley Transonic Dynamics Tunnel (TDT). The heavy gas test medium employed in the TDT allows simultaneous matching of full-scale Mach and Froude numbers at approximately one-quarter model scale. The low speed of sound of the heavy gas used in the TDT also permits model rotors to be rotated more slowly than would be required for Mach number matching in air. This in turn reduces centrifugal blade stresses, which simplifies model design tasks considerably. The Aeroelastic Rotor Experimental System (ARES)[35], which will be used to operate the active twist rotor model, is shown in the test section of the TDT in Figure 14. These wind-tunnel tests will serve as an important demonstration of the active twist rotor concept, and will provide valuable experimental data for validation of active twist rotor analytical tools.

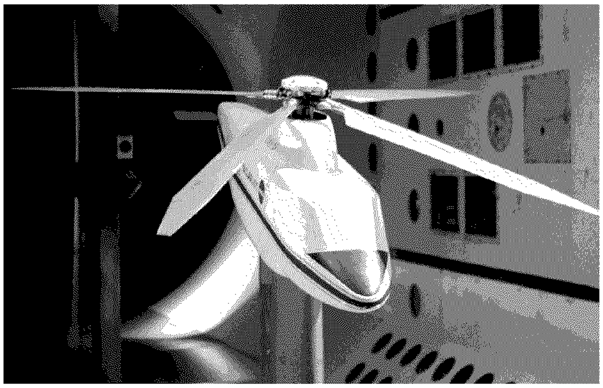

Figure 14: Aeroelastic Rotor Experimental System 9-foot diameter rotor testbed in the NASA LaRC Transonic Dynamics Tunnel.

The analytical and experimental activities described above are expected to form the foundation of a follow-on advanced active twist rotor research effort. This Future Technology Rotor (FTR) will incorporate advanced airfoils, planform geometry, and active twist capability in an optimized, integrated intelligent rotor blade structure. By considering active twist capabilities from the beginning of the rotor design process it should be possible to create an advanced rotor with aerodynamic performance, vibratory loads, and acoustic characteristics superior to that obtainable with purely passive-structure rotor blade designs.

4.3 APPLICATION COMMENTS

Several analytical and small- and large-scale experimental studies at the NASA Langley Research Center (LaRC) have demonstrated significant potential pay-offs by applying smart materials to practical problems. These pay-offs include reduced emissions and increased performance and safety using discrete piezoelectric patches and interdigitated electrode piezoelectric fiber composites (IDEPFC). While yielding notable results, these studies also highlight the need for critical advances in electrical, structural and aeroelastic modeling and testing to make these "smart applications" viable. In a new 6 year effort, NASA LaRC seeks to substantially advance the state of the art in smart materials technologies to fill the technology gaps, enabling a wide range of adaptive structural and aeroelastic applications of smart materials. This new effort will focus on developing the enabling technologies to apply discrete piezoelectric patches, THUNDER wafers, and IDEPFC to aircraft and rotorcraft. This research on the development of enabling technologies can be applied to a wide range of engineering applications.

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